GAMMA RAY DETECTORS HAVING IMPROVED SIGNAL-TO-NOISE RATIO AND RELATED SYSTEMS AND METHODS FOR ANALYZING MATERIALS IN AN OIL WELL

RELATED APPLICATIONS

[0001] This application claims the benefit of priority to U.S. Provisional Application Serial No. 60/461,801, entitled, "Gamma Ray Detectors Having Improved Signal to Noise Ratio And Related Systems And Methods" filed April 10, 2003, the disclosure of which is hereby incorporated herein by reference in its entirety.

FIELD OF THE INVENTION

[0002] The present invention relates generally to the analysis of materials in an oil well using gamma rays, for example, from neutron activation and, more particularly, to detectors having improved signal-to-noise ratio for analysis of gamma rays and related methods.

BACKGROUND OF THE INVENTION

[0003] The composition of a material can be analyzed based on the characteristics of the gamma rays detected by a gamma ray detector. For example, elements typically emit gamma rays at certain characteristic energies when activated with a suitable source of neutrons during neutron activation. Prompt Gamma Neutron Activation Analysis (PGNAA) and Neutron Inelastic Scattering (NIS) techniques have been used for measuring elemental composition in bulk samples. These techniques can produce high energy or highly penetrating gamma rays, which can allow the analysis of large sample volumes.

[0004] These techniques have been used to analyze materials in the context of oil well logging. In particular, the carbon/oxygen ratio may provide information about the relative amounts of oil or water in the well. The logging tool generally includes a fast neutron source and a radiation detector spaced apart from the source. The fast neutrons originating from the source collide with formation

elements. These collisions often result in the emission of inelastic gamma rays and, subsequently, the slowing down of the neutrons. Neutrons can also be slowed by elastic collisions with elements with small nuclei, such as hydrogen, carbon, and oxygen. Upon slowing down, the neutrons may be captured and another set of gamma rays may be emitted. The resulting gamma rays, either before or after neutron slowing, are detected by the radiation detectors and the resulting spectra are analyzed to obtain information about the elemental amounts in the formation. Carbon and oxygen generally emit gamma rays ranging from 4.44 to 6.13 MeV, which can result from the interaction of fast neutrons with these elements. Gamma rays ranging from 1.6 to 4.8 MeV can also be detected from carbon and oxygen as a result of the capture of primarily thermal neutrons by these elements.

[0005] The gamma ray detectors used in a logging tool are constrained in size because of the relatively small size of a borehole. The resulting spectrum may have a low signal-to-noise ratio, and therefore, the data may have poor statistical significance and be difficult to analyze.

SUMMARY OF THE INVENTION

[0006] According to embodiments of the present invention, a gamma ray detector assembly for placement in a logging tool in a borehole is provided. A first gamma ray detector is elongated along an axis and defines a void extending along the axis. A second gamma ray detector conforms to at least a portion of the void. The first and the second gamma ray detectors are configured to be positioned in the borehole.

[0007] In some embodiments, the first and second gamma ray detector are cylindrical. The first gamma ray detector forms an outer cylinder and the second gamma ray detector forms an inner cylinder. The first gamma ray detector can have a thickness that varies around the perimeter of the second gamma ray detector. In some embodiments, the thickness is uniform.

[0008] In certain embodiments, a shielding material is positioned on an end of the first gamma ray detector, and a radioactive neutron source is positioned on a side of the shielding material facing away from the first gamma ray detector. The radioactive source is configured to irradiate material in a borehole. The detector assembly may further include a first photomultiplier tube in communication with

the first gamma ray detector and a second photomultiplier tube in communication with the second gamma ray detector.

[0009] In particular embodiments, a signal processor is configured to receive signals from the first and second gamma ray detectors. The signal processor can be configured to detect a first event in one of the first and the second gamma ray detectors and to determine if a second event is detected in coincidence with the first event in the other of the first and the second gamma ray detectors. The signal processor can be configured to determine the rate of coincidence between an event in one of the first and second detectors and an annihilation photon in the other of the first and second detectors, the rate of coincidence between an event and two annihilation photons, and the rate of coincidence between a first event and a second event, wherein the first event and the second event sum to a predetermined energy. The predetermined energy can be between about 1.5 MeV to about 11 MeV. In some embodiments, the signal processor is configured to determine a ratio of oxygen and carbon based on events in the first and second gamma ray detectors.

[0010] According to method embodiments of the present invention, methods of detecting coincidence in gamma ray detectors in a borehole are provided. A first gamma ray detector and a second gamma ray detector are placed into a borehole. The first and second gamma ray detectors can be configured as described above. A first event is detected in one of the first gamma ray detector and/or the second gamma ray detectors. It is determined whether a second event is detected in coincidence with the first event in the other of the first and the second gamma ray detectors.

[0011] Coincidence counting techniques according to embodiments of the present invention may be made of entirely hardware, entirely software, or a combination of hardware and software embodiments.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] **Figure 1** is a schematic diagram of a gamma ray detector assembly according to embodiments of the present invention placed in a borehole of an oil well.

[0013] **Figure 2A** is a schematic diagram of the gamma ray detector assembly of **Figure 1** and a signal processor according to embodiments of the present invention.

[0014] **Figure 2B** is a schematic diagram of a gamma ray detector according to further embodiments of the present invention.

[0015] **Figure 3** is a cross sectional view of the gamma ray detector assembly of **Figures 1** and **2A** taken along the line **3-3** of **Figure 2A**.

[0016] **Figure 4** is a cross sectional view of a gamma ray detector assembly according to further embodiments of the present invention.

[0017] **Figure 5** is a cross sectional view of a gamma ray detector assembly according to still further embodiments of the present invention.

[0018] **Figure 6** is a flow chart illustrating operations according to embodiments of the present invention.

[0019] **Figure 7**is a graph illustrating a single events spectrum and a coincidence spectrum for a ^{24}Na sample for an inner detector according to embodiments of the present invention.

[0020] **Figure 8** is a graph of a two-dimensional representation of a three-dimensional spectrum for an inner and an outer detector for a ^{24}Na gamma ray source according to embodiments of the present invention.

[0021] **Figure 9** is a graph illustrating a single events spectrum, a total coincidence spectrum, and a 0.511 MeV coincidence spectrum for a ^{24}Na gamma ray source using an inner detector according to embodiments of the present invention.

[0022] **Figure 10** is a graph illustrating a total coincidence spectrum, a coincidence summation spectrum at 1.368 MeV, and a coincidence summation spectrum at 2.754 MeV for a ^{24}Na gamma ray source using diagonal summing techniques for an inner detector corresponding to the full energies of 1.368 MeV and 2.754 MeV according to embodiments of the present invention.

[0023] **Figure 11** is a graph illustrating a total coincidence spectrum, a coincidence summation spectrum at 1.368 MeV, and a coincidence summation spectrum at 2.754 MeV for a ^{24}Na gamma ray source using diagonal summing techniques using an inner detector and corresponding to the single escapes of the

1.368 MeV and 2.754 MeV gamma rays according to embodiments of the present invention.

[0024] **Figure 12** is a graph illustrating a 0.511 MeV coincidence spectrum and a 2.754 MeV summation spectrum for a ^{24}Na gamma ray source using an inner detector according to embodiments of the present invention.

[0025] **Figure 13** is a graph illustrating a single events spectrum, a total coincidence spectrum, and a 0.511 MeV coincidence spectrum for a ^{24}Na gamma ray source using an outer detector according to embodiments of the present invention.

[0026] **Figure 14** is a graph illustrating a single events spectrum, a total coincidence spectrum, and a 0.511 MeV coincidence spectrum for a sulfur sample using an inner detector according to embodiments of the present invention.

[0027] **Figure 15** is a graph illustrating a two-dimensional plot (flat view) of the counts in two NaI detectors for a Yttrium sample.

[0028] **Figure 16** is a graph illustrating a single events spectrum, a total coincidence spectrum, a 0.511 MeV coincidence spectrum, and a diagonal summation coincidence spectrum for a Yttrium sample according to embodiments of the present invention.

DETAILED DESCRIPTION OF EMBODIMENTS OF THE INVENTION

[0029] The present invention now will be described more fully hereinafter with reference to the accompanying drawings, in which preferred embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. In the drawings, like numbers refer to like elements throughout. Thicknesses and dimensions of some components may not be drawn to scale and may be exaggerated for clarity. It will be understood that when an element is referred to as being “on” or "adjacent" another element, it can be directly on or adjacent the other element or intervening elements may also be present. In contrast, when an element is referred to as being “directly on” another element, there are no intervening elements present.

[0030] As used herein, the term "event" refers to the detection of a gamma ray or gamma ray interaction. Two or more events may be caused by the same gamma ray.

[0031] A detector assembly **10** according to embodiments of the present invention is shown in **Figure 1**. The detector assembly **10** includes detectors **18**, **20** and photomultiplier tubes **16A**, **16B**. The detector assembly **10** is separated from a source **12** by a shielding material **14** such as lead. As illustrated, the source **12**, shielding material **14**, photomultiplier tubes **16A, 16B** and detectors **20** are enclosed in a housing **22**. Scintillation photons from detector **18** are received by photomultiplier tube **16A** and scintillation photons from detector **20** are received by photomultiplier tube **16B** to provide a signal indicating the detection of gamma ray events. The detectors **18, 20** and the photomultiplier tubes **16A**, **16B** can form an integrated detector device and the detectors **18**, **20** can be in contacting relationship with one another or the detectors **18**, **20** can be separated by a small space. The housing **22** is a substantially waterproof housing or logging tool that is designed for use in the borehole of an oil well, which may expose the detector assembly **10** to water and other fluids and high temperatures and/or high pressure conditions. Examples of logging tools used in a borehole environment are discussed in U.S. Patent No. 4,760,252 to Albats et al., the disclosure of which is incorporated herein by reference in its entirety. Although the detectors **18**, **20** and photomultiplier tubes **16A**, **16B** are shown with respect to the housing **22**, other configurations can be used. For example, the detectors **18**, **20** and photomultiplier tubes **16A**, **16B** can be integrated as part of other oil well logging devices, such as devices for measuring the gamma density, natural gamma rays, and/or the neutron porosity.

[0032] The detector assembly **10** and the housing **22** are configured so that it can be placed in a borehole **24**. As illustrated, the detector **20** is elongated along axis **Y-Y** and has a void **V** that extends along the axis **Y-Y**. The detector **18** is adapted to conform to the void **V**. In this configuration, the detectors **18, 20** are configured to be positioned in a borehole logging tool, which is generally cylindrical with an outer diameter of about three to six inches and a length as long as about thirty feet. For example, the detectors can be sized to fit into a circular

borehole, such as a borehole for an oil well. However, the detectors can be sized to fit into other types of boreholes. For example, boreholes in an oil well are typically between about six and about ten in diameter, and the logging tools are generally smaller than the borehole diameter. These boreholes may be several miles in depth. In some embodiments, the detector assembly **10** has a generally cylindrical shape with an outside diameter of about 1-and-7/8 inch and a length from about six to about twelve inches. As illustrated, the detectors **18**, **20** and the detector assembly **10** are elongated, *i.e.*, having more length than width. For example, the detector assembly **10** can have a length to width ratio of between about 1.5 to about 4 or 5 or more.

[0033] The detector assembly **10** can be used to analyze the composition of surrounding materials **26**. The detector assembly **10** can be mounted within an oil well logging device to facilitate the analysis of the surrounding materials **26**. Data from the detector assembly **10** can be analyzed, for example, to determine the carbon/oxygen ratio of the surrounding materials **26**. The carbon/oxygen ratio can be used as an indication of how much oil or water is present in the surrounding materials **26**.

[0034] In this configuration, gamma rays from neutron activation can be used to analyze material in an oil well. Embodiments of the present invention can incorporate coincidence-counting techniques that may improve the signal-to-noise ratio and reduce background in a dataset or spectrum. The effects of summing and pulse pile up may also be reduced. "Summing" and "pulse pile up" refer to coincidence events that are detected at approximately the same time in one detector. This results in a single higher energy event being recorded rather than two lower energy events. Summing is generally the result of gamma rays emitted from a source at the same time in true coincidence. Pulse pile up generally refers to random coincidence events from more than one source that randomly occur at the same time.

[0035] The source **12** can be a neutron source that emits neutrons. In some embodiments, the source **12** is a fast neutron source such as an accelerator source that produces neutrons with an energy of about 14 MeV. Examples of other neutron sources include Cf-252, Am-241-Be, and radium/beryllium sources. Neutrons from the source **12** undergo collisions with the surrounding materials **26**.

Without wishing to be bound by theory, these collisions may result in the emission of inelastic gamma rays and, subsequently, the slowing down of the neutrons. Upon slowing down, the neutrons may be captured, which may cause the emission of still more gamma rays. The gamma rays from these and other reactions may be detected by the detectors **18, 20** combined with the photomultiplier tubes **16A, 16B**. For example, the detector assembly **10** may include light insulating layers to isolate the detectors **18** from the photomultiplier tube **16B** and to isolate the detector **20** from the photomultiplier tube **16A**. In this configuration, scintillation photons from the detector **18** are received by the photomultiplier tube **16A** and scintillation photons from the detector **20** are received by the photomultiplier tube **16B**. Gamma rays can pass through the outside detector **20** and into the inner detector **18**. A material such as wax (not shown) may also be incorporated into the configuration shown in **Figure 1** in order to thermalize neutrons from the source **12**.

[0036] Gamma rays are generally detected when an incident gamma ray interacts with matter in a detector. A single gamma ray may result in multiple interactions or "events" in detectors **18, 20**. When more than one event occurs as the direct or indirect result of a single gamma ray in detectors **18, 20**, the timing of the events may indicate the relationship of the events to a single gamma ray. Such events may be detected in "coincidence." That is, when two or more events occur within a certain time range, typically between about 10 and about 100 nanoseconds (or less), the events can be defined as being in coincidence. For example, and again without wishing to be bound by theory, when an incident gamma ray undergoes an interaction in the inside detector **18**, a pair production interaction may occur. This interaction can deposit all of the gamma ray energy minus 1.022 MeV at the interaction site and produce two 0.511 MeV annihilation photons that are emitted in opposite directions. In such a reaction in the inside detector **18**, at least one of the 0.511 MeV annihilation photons may be detected in the outside detector **20** in coincidence with the deposition of energy in the inside detector **18**. Such pair production reactions may be more likely to occur as the incident gamma ray energy increases.

[0037] Any suitable detector can be used for the detectors **18, 20**. For example, detectors **18, 20** may be scintillating radiation detectors such as scintillating detectors including crystals such as NaI(Tl), LSO, BGO, KBr(Tl), NaBr(Tl), KI(Tl), KCl(Tl), CsI(Na), CsI(Tl) or polyvinyl toluene plastic scintillators. Scintillating radiation detectors typically utilize a photomultiplier tube to detect scintillation and amplify the resulting signal. The detectors **18, 20** may also be semiconductor detectors such as germanium or gallium nitride detectors. However, gallium nitride detectors normally have to be kept cooler than scintillation detectors. Such detectors may not require photomultiplier tubes **16A, 16B**, and therefore, the photomultiplier tubes **16A, 16B** may be omitted. In other embodiments, both detectors are scintillation detectors. Scintillation detectors may withstand the temperature conditions in an oil well borehole.

[0038] **Figure 2A** illustrates the detector assembly **10** from **Figure 1** in communication with a signal processor **30**. **Figure 3** is a cross-section of the detectors **18, 20** taken along line **3-3** in **Figure 2A**. The photomultiplier tubes **16A, 16B** amplify a signal from the gamma ray detectors **18, 20** and transfer the signal to the signal processor **30**. The signal processor **30** includes a coincidence counting module **32** and a memory **34**. The signal processor **30** is connected to a display **36**.

[0039] As illustrated in **Figure 3**, the detector **20** extends around the detector **18**. The detector **18** can be described as a cylinder that fits inside detector **20**. In some embodiments, the detector **18** is about one inch in diameter.

[0040] As illustrated in **Figure 2A**, signals that indicate events in the scintillation detectors **18, 20** are processed by the signal processor **30**. The coincidence counting module **32** can determine a coincidence counting rate by identifying events that are in coincidence, and coincidence and/or non-coincidence events can be recorded or stored in the memory **34**. The signals and/or events from the detectors **18, 20** can be stored in the memory **34** and processed at a later time. The signals can also be processed as they are received from the detector assembly **10** and subsequently stored in the memory **34**.

[0041] The coincidence counting module **32** can carry out operations according to embodiments of the present invention. For example, the coincidence counting

module **32** can read data from the memory **34** or from the detector assembly **10** in order to determine if events are coincidence events or if an event is a single event that is not in coincidence with other events. Although the coincidence counting module **32** is illustrated with respect to the processor **30**, other configurations can be used to carry out operations according to embodiments of the present invention. For example, the coincidence counting module **32** and/or the processor **30** can be incorporated into the detector assembly **10** or the coincidence counting module **32** may be incorporated into the memory **34**.

[0042] The display **36** may display raw data and/or data that has been processed or selected by the signal processor **30**. The display **36** may be part of the signal processor **30** or the display **36** can be a separate device. Data can be displayed by the display **36** in real time as the data is being collected, or it can be stored in the memory **34** and displayed at a later time. In some embodiments, the display **36** and/or memory **34** is omitted.

[0043] Other configurations of "inner" and "outer" detectors can be used such that the outer detector defines a void and the inner detector is configured to conform to at least a portion of the void. For example, the void can be a passageway with two open ends, a cavity with one open end, or a void entirely surrounded by the outer detector on all sides. A detector assembly **100** according to further embodiments of the present invention is shown in **Figure 2B**. The detector assembly **100** includes an inner detector **180** and an outer detector **200** relatively configured such that the inner detector **180** does not extend the entire length of the outer detector **200**. The detector **180** is in communication with the photomultiplier tube **160A** and the detector **200** is in communication with the photomultiplier tube **160B**. The detector assembly **100** can be positioned in a borehole, for example, as shown with respect to the detector assembly **10** in **Figure 1**. As illustrated in **Figure 2B**, the photomultiplier tubes **160A**, **160B** and the detectors **200** are enclosed in a housing **220**.

[0044] Although the detector assemblies **10, 100** are described herein as generally cylindrical, other shapes can be used. For example, other cross-sectional shapes can be used such as ovals, rectangles, squares and the like.

[0045] Further examples of alternative detector arrangements are shown in **Figures 4** and **5**. **Figure 4** illustrates an outside detector **20A** that extends around a portion of inside detector **18A**. As shown in **Figure 5**, an outside detector **20B** extends around an inside detector **18B**. The outside detector **20B** has a reduced thickness at a portion **38**. The portion **38** can be integrated with the outside detector **20B** or provided as a separate detector piece.

[0046] Other detector configurations may be used. For example, three or more detectors may be combined in a detector assembly and coincidence events in two or more detectors can be identified.

[0047] Operations according to embodiments of the present invention are shown in **Figure 6**. Such operations may be carried out, for example, by the coincidence counting module **32**. An event is detected (Block **70**), for example, by the detector assembly **10 (Figures 1** and **2A)** or the detector assembly **100 (Figure 2B)**. If an event is detected as a coincidence event (Block **72**), the event or events are identified as a coincidence events (Block **74**). These events can be included in a coincidence dataset. If a coincidence event is not detected (Block **72**), then the event is a single event (Block **76**). Single events can be stored in memory (such as memory **34** in **Figure 1**) and/or displayed. Alternatively, single events may be discarded from the dataset.

[0048] Various coincidence counting techniques and/or parameters for counting coincidence events may be used. Examples of coincidence counting parameters include the total coincidence, coincidence between any event and an annihilation photon event, and coincidence between events that sum to a predetermined energy. However, any subset of events in one detector can be selected and events that are in coincidence with the selected subset can be identified. The total coincidence between two detectors includes all events in one detector that are in coincidence with the other detector. Coincidence between any event and an annihilation photon includes events in one detector that are in coincidence with an annihilation photon in the other detector. Annihilation photons are produced when a positron annihilates, producing two 0.511 MeV photons. Coincidence summing to a predetermined energy include events in one detector that are in coincidence with events in another detector only if the energy of the two events sum to a predetermined energy level. Typical energy ranges are between and about 0.5 and

about 11 MeV for the configuration shown in **Figures 1** and **2A-B**. For example, gamma ray energies from carbon and oxygen are 4.44 MeV and 6.13 MeV, respectively. Depending on detector resolution, these peaks may be detected in various energy ranges. For example, the carbon 4.44 MeV peak is typically detected in a range between about 4.2 and about 4.6 MeV for a NaI detector and between about 4.35 and 4.45 in a Ge detector due to increased resolution in a Ge detector. The 6.13 MeV oxygen peak is typically detected in a range between about 5.9 MeV and about 6.3 MeV in a NaI detector and between about 6.05 MeV and about 6.2 MeV in a Ge detector.

[0049] In certain embodiments, an outside "well" detector, such as detector **18** in **Figure 1**, can have an outside diameter of about 1-and-7/8 inches and a length from about 2 to about 6 inches. The outside well detector can have a void or "well" with a diameter of about one inch. The inside "well-filling" detector, such as detector **20** in **Figure 1**, can be configured to fill the inside of the one inch diameter well. These two detectors can be operated in coincidence so that only those detector pulses that occur simultaneously or within a certain time range are recorded or identified as being in coincidence. For example, these techniques may be used to detect relatively high gamma ray energies from carbon and oxygen, which are of interest in oil well logging operations. The energies of gamma rays from carbon and oxygen are 4.44 MeV and 6.13 MeV, respectively. Gamma rays produced by other elements and/or at other energy levels may also be detected. For example, the detection of silicon and calcium gamma rays may also be performed. Primary interactions of these gamma rays may be pair production reactions. There is a relatively high probability that one or both of the annihilation photons produced in pair production will be detected in the outer "well" detector if the initial interaction is in the inner well-filling detector. The initial interaction may deposit an energy equal to the full gamma ray energy minus 1.022 MeV or 0.511 MeV at the interaction site. These peaks may be called first and second "escape peaks." These events may occur at approximately the same time or within a selected time frame. Therefore, coincidence counting of these events (e.g., an escape and one or two 0.511 MeV photon interactions) may record these energies with reduced noise.

[0050] A coincidence device such as a Sparrow™ system (commercially

available from Sparrow Corporation in Port Orange, FL, U.S.A.) may be used that is capable of recording individual spectral counting rates from each detector while also recording the coincidence counting rates that occur at specific energies from each detector. This latter data may include three-dimensional data and provide the counts or counting rate as a function of the energy deposited in one detector that is in coincidence with energy deposited in a second detector at substantially the same time or within a specified time frame. From this three-dimensional data (counts as a function of energy in both detectors), those pulses that satisfy a predetermined coincidence criteria, such as adding to a prescribed energy, can be extracted. For example, either the carbon gamma ray energy (4.44 MeV) or the oxygen gamma ray energy (6.13 MeV) can be used. This can be used to produce a spectra that contains, for example, substantially only the first and second escape peaks of the carbon and/or oxygen energies along with the 0.511 MeV and the 1.022 MeV peaks. This may result in an improved spectrum with reduced noise. The reduction of signal due to coincidence counting may be relatively small.

[0051] Embodiments of the present invention will now be described with respect to the following non-limiting examples.

Example 1: Sodium-24 Study

[0052] A ^{24}Na radioactive gamma ray source was placed adjacent the detector assembly **100** shown in **Figure 2B**. ^{24}Na decays by emitting two well separated gamma rays of energies 1.368 and 2.754 MeV. Both of these gamma ray energies are above the threshold (1.02 MeV) of the pair production effect. Portions of the data obtained are illustrated in **Figures 7-13**.

[0053] The ^{24}Na source was placed approximately 10 cm away from the center of the detectors to simulate radiation incident on the sides of the detectors as may be obtained in oil well logging applications. Because ^{24}Na is radioactive, a neutron source was not required or used. **Figure 7** shows the obtained singles and total coincidence spectra.

[0054] As can be seen in **Figure 7**, the total coincidence spectrum is approximately 2-3 times lower than the singles spectrum. The effects of summing and pulse pile up can be reduced. This may provide a higher detection sensitivity.

[0055] In some embodiments, information may be reduced using coincidence

spectra because the coincidence spectra illustrate the detection of events related to only one gamma ray in coincidence. Thus, the full energy peak can be lost and numerous energy combinations that sum to the full energy peak may be obtained.

[0056] **Figure 8** shows the two-dimensional spectrum obtained when using the ^{24}Na source. Certain features are labeled on **Figure 8** and described in Table 1.

[0057] Based on the different features in the two-dimensional spectrum of **Figure 8**, various projections and resulting spectra can be obtained. The first projection is a vertical projection corresponding to the 0.511 MeV energy range in the outer "well" detector (such as detector **200** in **Figure 2B**) and is shown in **Figure 9**. For comparison, the single event and total coincidence spectra are shown together in **Figure 9**. It can be seen that the escape peaks of the 2.754 MeV and 1.368 MeV gamma rays appear with a high signal-to-noise ratio. The 0.511 MeV coincidence spectrum is almost an order of magnitude less than the single event spectrum.

[0058] **Figure 10** shows the two diagonal summing spectra corresponding to the full energies of the 1.368 MeV and 2.754 MeV gamma rays. The shape of the spectra can be described by the comments on the first and second features in Table 1. Although there are no distinct peaks in the spectra presented in **Figure 10**, one can still make use of this "V-shaped" data. This data may be analyzed using a Library Least Squares (LLS) analysis because of its well-defined characteristic shape. The data shown in **Figure 9** is almost the same intensity as the total coincidence on the right hand (high energy) side of the spectrum.

[0059] **Figure 11** illustrates the two-dimensional diagonal summing spectra corresponding to the single escapes of the 1.368 MeV and 2.754 MeV gamma rays. The shape of the spectra can be described by the comments on the third and fifth features in Table 1. For comparison purposes, the 0.511 MeV coincidence spectrum and the 2.754 SE diagonal summing spectrum are shown in **Figure 11**.

Table 1: Na-24 Two Dimensional Spectrum Features Using the New NaI Detector Arrangement

#	Peaks Correspond to in the		Comment
	Well Detector	**Inside Detector**	
[1]	Backscatter gamma	Compton Edge of the 2.754 MeV gamma ray	The spread around the peak is caused by the wide range of angles that the gamma ray can scatter through, not just 180 degrees
[2]	0.511 MeV Annihilation gamma ray	Single escape of the 2.754 MeV gamma ray	Note how this feature and the first feature fall on the same diagonal line. This line corresponds to the 2.754 MeV sum.
[3]	Low energy gamma rays	High energy gamma rays, below the Compton Edge and above the double escape of the 2.754 MeV gamma ray	This feature lies on a diagonal line. This means that it corresponds to a certain energy sum, the double escape of the 2.754 MeV gamma ray. This feature is observed because of the partial energy deposition of the 0.511 MeV annihilation gamma ray in the inside detector before being completely detected by the Well detector
[4]	Low energy gamma rays	Double escape of the 2.754 MeV gamma ray	This feature is similar to the third feature except that there is no energy deposition in the inside detector by the 0.511 MeV annihilation gamma ray, only in the Well detector
[5]	0.511 MeV Annihilation gamma ray	Double escape of the 2.754 MeV gamma ray	The diagonal line joining this feature and the third feature corresponds to the Single escape energy sum of the 2.754 MeV gamma ray.
[6]	Backscatter gamma	Compton Edge of the 1.368 MeV gamma ray	Same comment as first feature.
[7]	0.511 MeV Annihilation gamma ray	Single escape of the 1.368 MeV gamma ray	Same comment as second feature, but for the 1.368 MeV gamma ray.
[8]	0.511 MeV Annihilation gamma ray	Double escape of the 1.368 MeV gamma ray	Same comment as fifth feature, but for the 1.368 MeV gamma ray.

[0060] The spectra extracted from the outer "well" detector (such as detector **200** in **Figure 2B**) may be similar to those from the inner detector (such as detector **180** in **Figure 2B**) for this energy range. These spectra may be less useful for the following reasons: 1. The outside "well" detector has a NaI base. This base may yield a higher light collection than the sides of the detector. This results in "Double Peaks" in the spectrum where each distinct gamma energy is represented by two peaks in the spectrum. 2. The detection efficiency of the outside "well" detector may be low for high energy gamma rays. This may be a consequence of the size of the outer "well" detector.

[0061] Examples of the spectra obtained from the outer "well" detector are shown in **Figure 13**. Two peaks that correspond to the 2.754 MeV gamma ray can

be seen in the singles spectrum at approximately channels 1380 and 1510.

Example 2: Sulfur Study

[0062] A natural sulfur sample was placed approximately 25 cm away from the center of a detector assembly, such as detector assembly **100** of **Figure 2B**, in a thermal neutron beam produced by the PULSTAR educational reactor at North Carolina State University. The PULSTAR reactor is a 1 MW pool-type research reactor with 4% enriched, pin-type fuel consisting of uranium dioxide pellets in zircaloy cladding.

[0063] The main isotope in natural sulfur is ^{32}S which, when activated by neutrons to $^{33*}S$, decays by emitting gamma rays with a wide energy range. A 5.4205 MeV gamma ray results from the decay of $^{33*}S$. The 5.4205 MeV gamma ray falls in the energy range of interest for oil well logging applications.

[0064] **Figure 14** illustrates the singles, total coincidence, and 0.511 MeV coincidence spectra in the inside detector (such as detector **180** in **Figure 2B**). The escape peaks of the 5.4205 MeV gamma ray are shown in the 0.511 MeV coincidence spectrum at 4.909 and 4.398 MeV.. The escape peaks of the hydrogen 2.223 MeV gamma ray also show in the spectrum. This should not be a concern as this detector arrangement may also be used to detect higher energy gamma rays than the hydrogen gamma ray.

Example 3: Yttrium

[0065] An yttrium sample was placed in a thermal neutron beam provided by the PULSTAR reactor. The sample was placed approximately 20 cm away from the center of a detector assembly, such as the detector assembly **100** shown in **Figure 2B**, to simulate radiation in an oil well. **Figure 15** is a two-dimensional plot (flat view) of the event counts in both a NaI outside "well" detector (such as detector **200** in **Figure 2B**) and the inside detectors (such as detector **180** in **Figure 2B**). **Figure 16** illustrates a single detector, total coincidence, 0.511 MeV coincidence spectra, and the diagonal summing spectra that were obtained in the inside detector. The 0.511 MeV coincidence spectrum was obtained by extracting the spectrum from the two-dimensional array in the inside detector corresponding to the 0.511 MeV energy range in the outside "well" detector. The diagonal

summing spectrum was obtained by projected the spectrum corresponding to the outlined diagonal energy window in **Figure 15** to the inside detector. The diagonal window corresponds to an energy of 6.079 MeV. This is the energy of the most intense gamma ray resulting from the capture of thermal neutrons by yttrium.

[0066] As illustrated in **Figure 16,** the escape peaks of the 6.079 MeV gamma ray appear with a high signal-to-noise ratio in the 0.511 MeV coincidence and diagonal summing spectra as compared to the single detector and total coincidence spectra.

[0067] The foregoing is illustrative of the present invention and is not to be construed as limiting thereof. Although a few exemplary embodiments of this invention have been described, those skilled in the art will readily appreciate that many modifications are possible in the exemplary embodiments without materially departing from the novel teachings and advantages of this invention. Accordingly, all such modifications are intended to be included within the scope of this invention as defined in the claims. Therefore, it is to be understood that the foregoing is illustrative of the present invention and is not to be construed as limited to the specific embodiments disclosed, and that modifications to the disclosed embodiments, as well as other embodiments, are intended to be included within the scope of the appended claims. The invention is defined by the following claims, with equivalents of the claims to be included therein.